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Localization of Radiating Sources along the Hull of a Submarine Using a Vector Sensor Array

Joseph A. Clark and Gerald Tarasek
Naval Surface Warfare Center, Carderock Division
9500 MacArthur Blvd
West Bethesda, MD 20817-5000 USA

Abstract- **Mappings of sound sources on submarine hulls provide an important diagnostic tool for analyzing the radiated signature, and evaluating noise deficiencies and silencing improvements of U.S. Navy submarines. The acoustic imaging problem is particularly difficult because the resolution of signals required to provide useful information is usually on a scale that it is several times smaller than the acoustic wavelength. Recent testing with acoustic vector sensors (combined pressure and particle velocity sensors) has demonstrated that these devices can provide substantial improvements in source resolution over currently available pressure sensor arrays. The algorithms used to process data from arrays of vector sensors (tri-axial particle velocity sensors combined with pressure sensors) will be described and acoustic intensity images produced by simulated radiation from submarine hulls during recent testing at SEAFAC, the U.S. Navy acoustic signature measurement facility in Behm Canal, Alaska, will be presented.**

I.   INTRODUCTION

The US Navy has recently tested the performance of an array of vector sensors for radiated noise and source localization measurements. This paper will describe the construction of the array and the source localization experiments conducted at SEAFAC, the Navy's acoustic signature measurement facility near Ketchikan, Alaska.

II.   ARRAY CONSTRUCTION

Construction details of the vector sensor array are shown in Fig. 1. Type TV-001 miniature vector sensors constructed by Wilcoxin Corporation were used for the test. Each sensor contains one hydrophone and three accelerometers arranged in a triaxial configuration and mounted in a neutrally buoyant package approximately 1.5 inches in diameter and 2.5 inches long. Five sensors were mounted 4 inches apart in a tubular housing similar to those used for towed arrays.

III. TEST FACILITY

The location of the test site is shown in Fig. 2. The site is a deep, quiet fjord in southeast Alaska. Fiber optic links carry signals from the test location to data processing facilities on the beach. Currents are usually less than 0.1 knot in the

deep water. The calm weather during the tests typically provided sea state one conditions.
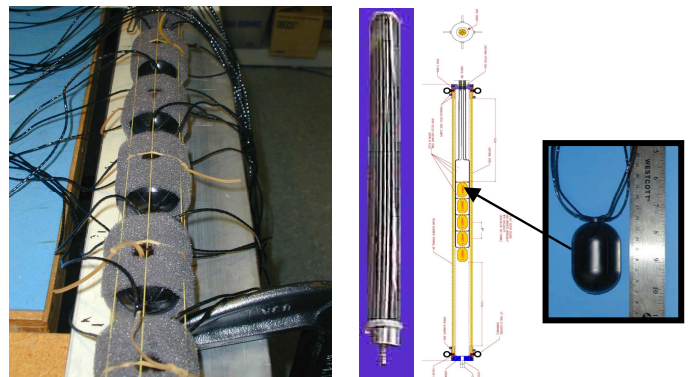

Figure 1. Vector sensor elements and array at several stages of assembly

The test was conducted off a barge located at the static site as shown in Fig. 3. (No submarine was present for the tests reported in this paper.) The vector sensor array and an omnidirectional sound source were suspended 99 ft apart at a depth of 400 ft. below the barge. The sound source was a model ITC-1032 spherical transducer. The major axis of the
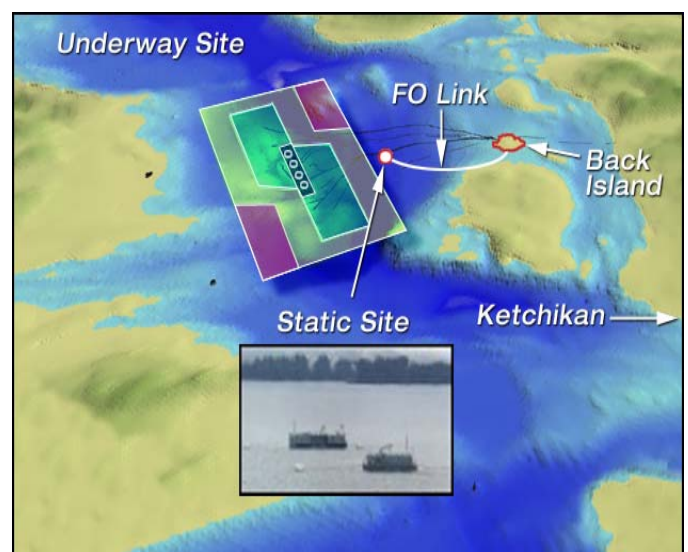

Figure 2. SEAFAC Acoustic Signature Measurement Facility

sensor array was oriented vertically. The horizontal orientation of the array was checked by the measuring the angle to the sound source. Small rotations of the array could be detected from these measurements.
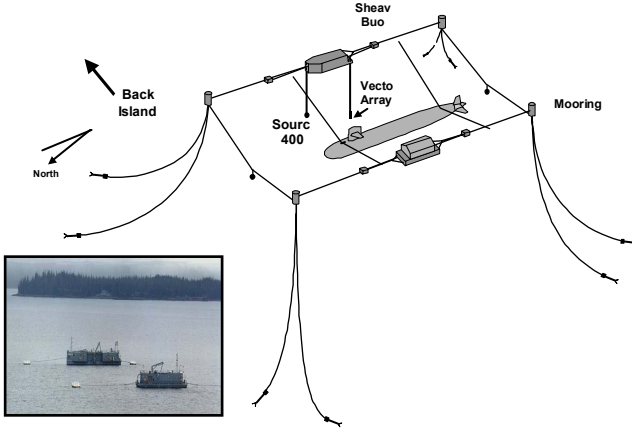

Figure 3. Test setup at SEAFAC static site

IV. DIRECTIVITY OF VECTOR SENSORS

Directional characteristics of a single vector sensor are illustrated by the beam patterns shown in Fig. 4. The omnidirectional response of the hydrophone element and the dipole response of the accelerometers are shown. Summation of the two responses produces the cardiod forms. An unweighted sum of the two responses produces the single lobed pattern. A weighted sum can be selected to maximize the directivity of the single sensor response at the cost of a smaller second lobe in the response pattern.

Omni-directional
(Conventional Response)
0 dB DI

Dipole Response
(accelerometers)
4.8 dB DI

Cardioid
(Omni + Dipole)
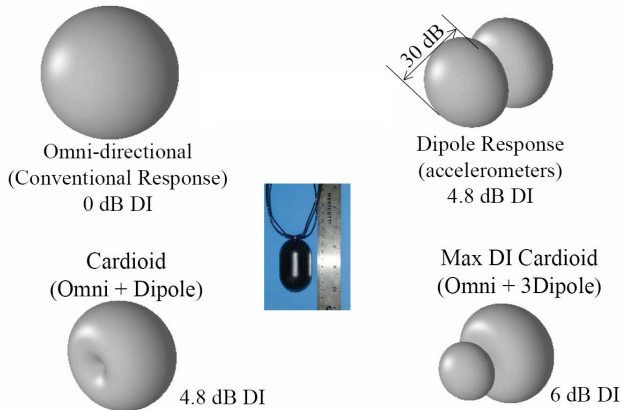4.8 dB DI

Max DI Cardioid
(Omni + 3Dipole)
6 dB DI

Figure 4. Beam Patterns of single sensors

Measured directional responses of the 5 element vector sensor array are shown for four processing cases in Fig. 5. Processing of signals from the hydrophone elements alone produces the donut-shaped pattern with vertical directivity but no horizontal directivity. The array of accelerometer elements

alone produces the dipole-like pattern, which indicates some horizontal directivity, but an ambiguity in direction of maximum response can be noted. Processing of the combined signals produces a beam pattern which reduces or eliminates this ambiguity.
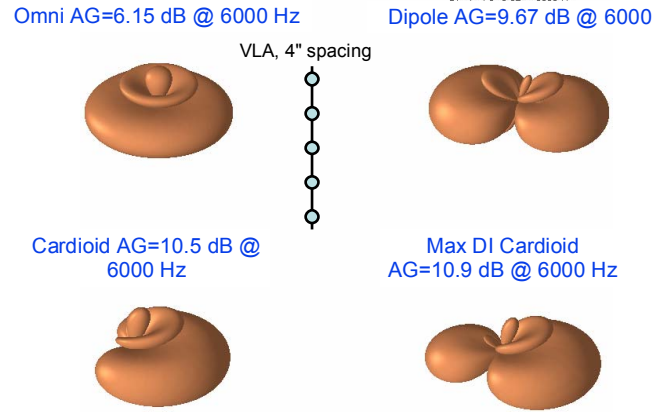

Omni AG=6.15 dB @ 6000 Hz

Dipole AG=9.67 dB @ 6000

VLA, 4" spacing

Cardioid AG=10.5 dB @ 6000 Hz

Max DI Cardioid AG=10.9 dB @ 6000 Hz

Figure 5. Beam Patterns of vector sensor array

V. SOURCE LOCALIZATION

Localization of a sound source on the hull of a submarine is achieved by comparing different accelerometer component responses as illustrated in Fig. 6. The three accelerometer component responses can be steered by appropriate processing to a reference direction. The tangent of the vertical angle to a localized sound source is computed from the ratio of the vertical component of the acceleration to the component in the reference direction. The horizontal angle is determined similarly.
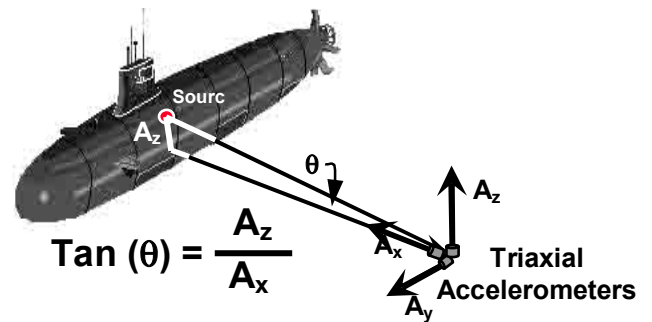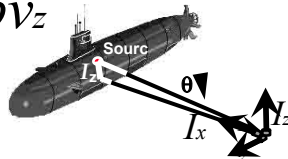

$$\text{Tan}(\theta) = \frac{A_z}{A_x}$$

Figure 6. Principle of Source Localization with Vector Sensors

Fig. 7 illustrates that the accuracy of source localization measurements is limited by the signal-to-noise ratio of the array rather than the wavelength as in conventional imaging systems. High angular resolution can thus be achieved with the vector sensor array if a priori information is available that only one localized source is present in a frequency band of interest. The high angular resolution can be achieved even at very low frequencies (corresponding to

acoustic wavelengths much longer than the spatial resolution of the localization measurement).

$$I_x = pv_x \; ; \quad I_z = pv_z$$

$$\theta = \arctan\left(\frac{I_z}{I_x}\right) \cong \frac{I_z}{I_x} = \frac{I_{zsignal} + I_{znoise}}{I_{xsignal} + I_{xnoise}}$$

$$\Delta\theta \cong \frac{I_{znoise}}{I_{xsignal}}$$

Figure 7. Accuracy of Source Localization Measurements

In the case of multiple sources simultaneously present in a single frequency band, a narrower response beam pattern is also required. This requirement is illustrated in Fig. 8. Narrower beam patterns such as the one illustrated in the figure are obtained by raising the weighting vector in the beam processing algorithm to a high power.
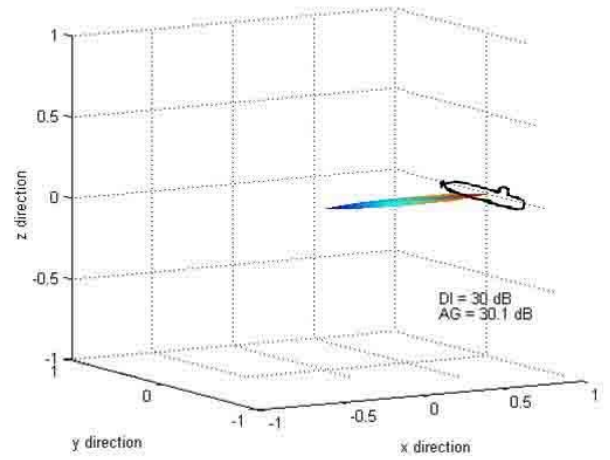

Figure 8. Simulation of highly directive beam pattern required to distinguish multiple localized sound sources

Angular measurements of localized sources are converted to spatially resolved maps by combining the vector sensor data with measurements of the distance from the array to the submarine hull. A simulated example of a spatially resolved source is shown in Fig. 9.
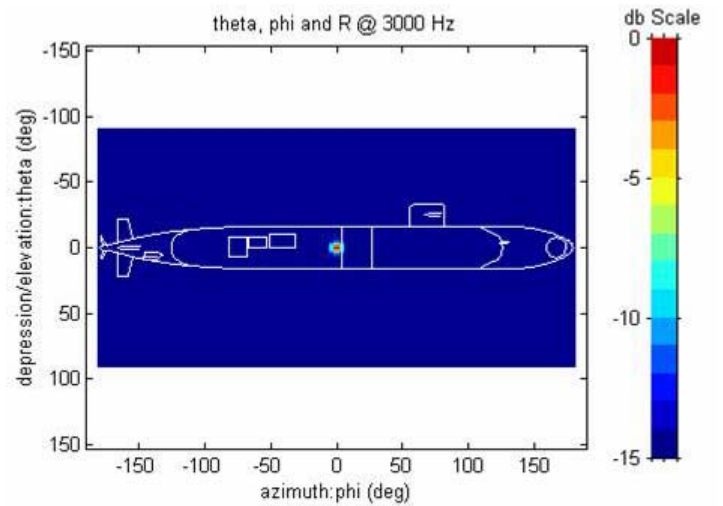

Figure 9. Display of simulated source localized on a submarine hull